

NGR-05-017-019

FINAL



FINAL REPORT
ON
A STUDY OF THE METHODS FOR THE PRODUCTION
AND CONFINEMENT OF HIGH ENERGY PLASMAS

by

Dr. Dah Yu Cheng, Principal Investigator
Mr. Peter Wang, Research Assistant

April 1, 1972 - September 30, 1972

(NASA-CR-140443) A STUDY OF THE METHODS
FOR THE PRODUCTION AND CONFINEMENT OF
HIGH ENERGY PLASMAS Final Report, 1

N74-34200

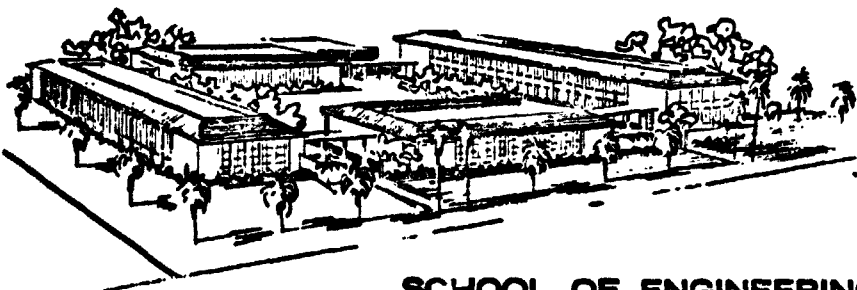
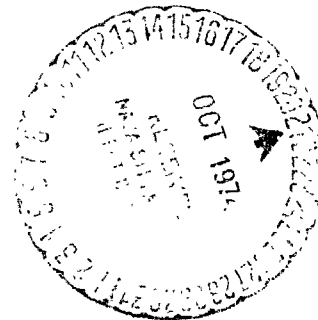
Apr. - 30 Sep. 1972 (Santa Clara Univ.)

29 p HC \$4.50

CSCL 201

G3/25

Unclas
50838



SCHOOL OF ENGINEERING

ENGINEERING AND APPLIED SCIENCE RESEARCH

UNIVERSITY OF SANTA CLARA

SANTA CLARA, CALIFORNIA AREA CODE 408 -984-4325

In the final six-month period our efforts have been concentrated on the experiments of injecting plasmas into a long B_z magnetic field from both ends of the field coil. The field lines ordinarily are straight in the center section of the coil. Due to the diamagnetic property of the plasma, once the plasmas have penetrated the field, they push the field lines outward to form a self-imposed mirror configuration. In most cases the mirror configuration is very stable. In the past, the magnetic mirror of the plasmas had been shown to be stable and never had gross instabilities been found. However, the previous experiments were conducted with large radius magnetic field coils and low density plasmas. In these conditions, the field coil had to be large in order to accommodate the large gyroradii of the electrons to avoid their collision with the vacuum walls. The collision of two low-density plasma beams injected from both ends of a B_z field would have no merit because the scattering cross section of the low-density plasma is so small that most of the beams pass each other without any interaction. The only way to trap the low-density plasma is to increase the magnetic field strength at both ends after the plasmas are inside the coil. The magnetic flux lines will be bent at the ends so that $\vec{J} \times \vec{B}$ force becomes large. This creates a reflection until the plasmas convert their kinetic energy into thermal energy (Fig. 1). Confinement time of such a plasma experiment up to 30 milliseconds with a plasma density of $10^{12}/\text{cc}$ was found feasible (Ref. 1), but the $n\tau$ product was still low.

The problem of stability under high density conditions is not known. However, the feature of no current flowing along the

B lines is still true, hence there is no reason to believe that the higher density would be unstable. If this is true, then not of such an experiment can be significantly improved with high plasma density. One of the fundamental problems of plasma injection experiments is the focus of the plasma beam to the opening of the B_z field where the B lines are very much curved. Unless the plasma can be concentrated in the neighborhood of the center line of the magnetic field, the majority of the plasma will be reflected back. This not only requires the plasma beam to be small and dense but also their thermal energy (random motion) is required to be much less than the kinetic energy of the injection. This rules out the use of a snow-plow accelerator as the plasma thus produced will not be able to confine itself to a small diameter and the thermal energy is in the same order as the kinetic energy. In the past, a Titanium washer gun was used for such an experiment and D_2 plasma was produced halfway inside the B_z field. In our experiment, we developed a deflagration plasma gun in the earlier periods of this study to meet the requirements of the injection experiments. We are now able to inject two plasma blobs from both sides of the B_z field in such a way that the plasma is very dense and the beam diameter is small. The B_z field then could guide the plasma beams to a hydrodynamic collision. It was found that the diamagnetic property of the plasma did push out the B lines to form a magnetic bottle mirror configuration. Once the kinetic energy was converted into thermal energy due to collision, the trapping process of the magnetic bottle was completed. Before the start of our experiments and sometimes due to the lack of data of the collision cross section, we wondered whether or not the

plasmas would pass each other anyhow, regardless of the high plasma density. This brings up a list of questions to be answered from our experiment:

- (1) Would the plasmas pass each other?
- (2) If the plasma is confined in the bottle configuration by collision, how stable would the plasma be and how long is the confinement time?
- (3) What would be the way to estimate the plasma density and the radius of the confined plasma?
- (4) Is it possible to do the injection experiment without giant machines?

To answer these questions, we can only begin from the fact that we had to do the experiment with small machines under the financial level of the current grant. The rest of the questions had to be found during the experiments. Steps leading to the current experiment will be discussed in the following sections:

(1) Deflagration plasma gun and continuous flow Z-pinch

As mentioned above, an ideal plasma injector is required for the injection experiment so that the injector is capable of producing a high velocity plasma at very high density, and with the smallest possible beam diameter. Such a device (Fig. 2) was developed during the previous years of this study, known as the deflagration plasma gun (Refs. 2, 3, 4). The plasma beam generated by this gun has a high density, high velocity and small beam diameter. The velocity of the plasma has been reported in the past (Ref. 2). The density and the diameter of the beam were known to be favorable for injection experiments but without accurate measurements. During this six-month period, a laser

interferometer system, reported in the last progress report, was used to measure the plasma density and the beam diameter as a function of time. The formation of the high density plasma beam found in this process is called the continuous flow Z-pinch. The possibility of such a phenomenon was postulated first by Morozov in 1967 (Ref. 5) but the shaped electrode coaxial accelerators in Russia (Refs., 6,7,8) failed to produce that phenomenon experimentally. This was due to their lack of knowledge about the deflagration process. With the laser system, the formation of the high density plasma beam was photographed as shown in Fig. 3. The distinguished features of the continuous flow Z-pinch are:

- (a) The beam has a very high density with a very small diameter.
- (b) The boundary of the beam is in a divergent straight line.
- (c) The continuous cumulation of the plasma makes the higher density away from the electrode.
- (d) The lifetime of such a beam can be longer than 7μsec.

The center electrode shown in Fig. 3 is a 1.25 cm diameter hollowed copper tube. The density in the high density beam is greater than 10^{18} /cc which is higher than anticipated. The beam is shown to be less than 0.50 cm. From this data, the deflagration gun has proven to be the most valuable device in doing the plasma injection experiments.

(2) Possibility of a continuous flow Z-pinch fusion reactor

Morozov (Ref. 5) postulated that a magnetized plasma flow in a convergent channel could lead to a high plasma density beam in a continuous fashion, but such a phenomenon cannot be produced in a snowplow gun. Morozov's theory would apply if the plasma is

flowing under the deflagration process. Since we have produced such an effect experimentally, the question of the feasibility of the current device alone as a fusion reactor could be asked again, but the device is small and the energy used for discharge is also small. If the device could be increased both in size and in energy storage capacity, it would then be possible to produce a 10^{19} /cc plasma beam in a quasi-steady state condition for over 30 μ sec. This plasma would have an nr value over that of the Lawson criteria. If the convergent angle could be shaped, a higher temperature in the pinch would also be expected.

(3) Inverted B_z field

Ordinarily, a magnetic field is constructed with a high μ iron core to increase the magnetic field strength. The field lines, however, have to pass the surrounding low μ space (Fig. 4a). The confinement field in this experiment inverted the high μ material to the outside space, thus creating two effects: first, it improved the magnetic field strength as the ordinary field; and, second, it forced the entrance of the field line to open much more rapidly (Fig. 4b). The flux lines at the entrance were bent further back to facilitate the injection of the plasma. The magnetic field was powered by truck batteries. The peak current, up to 1874 amperes, had been reached in a 160 turn coil. This corresponded to a field intensity of 9.1 kilogauss.

(4) Injection experiments

The set up of the injection experiment is shown in Figs. 5 and 6. The two gun nozzles were separated 218.2 cm apart. The magnetic field was mounted in the middle section. The vacuum

tube is only 6.03 cm in diameter with diamagnetic coil wound on the outside approximately 10 cm apart. Light pipes were located adjacent to the diamagnetic coils. The light pipes were gathered into a terminator in front of Image Converter Camera No. 1. The camera was operated under a streak mode, so that the radiation from the plasma could be photographed as a plot of the position and time. The No. 2 Image Converter Camera viewed the entrance region on the No. 2 gun side. The silver activated neutron counter was used to count the total number of neutrons, and a plastic scintillating counter was used to measure the time resolved neutron pulses.

The synchronization of the two plasma deflagration guns were found to be difficult and easy at the same time. The difficulty resulted from the discharge which can only be triggered by the high density neutral gas injection into the electrode spacing. The slowness of the neutral gas flow cannot be controlled accurately to within one microsecond even when the valve openings are completely synchronized. Fortunately, the high velocity, low-density plasma front (they were produced before the continuous Z-pinch was formed) of whatever the first discharged gun was flowing through the whole length of the experiments to induce a discharge in the second gun even before the second gun had enough neutral gas to initiate a self triggered discharge. The time delay for the two guns usually was only half to one microsecond; hence, this made synchronization easy. However, under these conditions the collision of two high energy plasma fronts cannot be performed inside the magnetic field. From the synchronization

data, the plasma front recorded a velocity of 2.5×10^8 cm/sec to 5×10^8 cm/sec. This can be verified by putting a partition between the guns--the discharges can no longer be synchronized. The plasma front is not the electron percussion wave since the percussion wave usually travels at a velocity close to half the speed of light.

The collision of the two plasma beams can be observed from the streak pictures (Fig. 7). The streak camera was triggered by the light emission at Gun No. 1, which usually discharged first. The pictures in Fig. 7a show that the fast plasmas meet each other at 3.5 μ s. This collision did not result in a sharp increase in radiation intensity. The slower and denser plasma beams met at 6.3 μ s. This high density plasma collision created a sudden increase in radiation. The pictures in Figs. 7b and 7c are the delayed 5 μ s and 15 μ s, respectively. The bright image of the radiation between diamagnetic coils indicated a continuous buildup of the plasma followed by a gradual decay after 25 μ s. It is also noticed that the snowplow plasma arrived at the light pipe between the diamagnetic coils, Nos. 15 and 16, about the same time. The velocity of this second plasma blob is only 2.5×10^6 cm/sec. The streaked picture did indicate a long confinement time.

To verify the timing of events that the current traces, diamagnetic probe signals are shown in Fig. 8. The gun current traces indicate that synchronization is accurate to within 0.5 μ s. The diamagnetic coil No. 4 is located just outside the field entrance, which is 66 cm from the Gun No. 2 muzzle. The earlier signal indicated the fast plasma passing this location

without too much scattering by the field lines. The plasmas started to cumulate at Coil No. 5, which was just inside the magnetic field. The plasma passed the No. 5 coil 7 μsec after the initiation of the discharge. The signal level was still low until collision took place between Coil Nos. 6 and 7. The sudden cumulation of plasmas made the signal to show a sudden jump. Two things happened simultaneously; first, the high plasma pressure started to reflect some plasma backout but this is attenuated by the continuous flow of plasma as can be seen from the straight line build-up signal of diamagnetic Coil No. 5. Second, a magnetic bottle was formed which tends to bounce the plasma blob back and forth between Coil Nos. 6 and 7. This phenomenon can be seen on the signal traces and the image converter streak picture which was delayed 25 μsec after the gun discharge was initiated. This delayed streak picture was made to cross check the location of the plasma blob in the bottle configuration with coil signals and the decays of the plasma blob density. The neutron trace showed that the fast plasmas collided between 4 to 5 μsec after current initiation; this corresponded to the streak picture in Fig. 7. A burst of neutron indicated by point (4) coincided with the jump in signals of the diamagnetic coils, and then the bouncing of the plasma along the z-direction in the bottle configuration coincided with bursts of neutrons at each reflection, which lasted until pointer (5). If one counts the total effective confinement time by the neutron production period, it is 12 μsec . The profiles of plasma pressure at different times and locations are presented in Fig. 9. The profiles also show that the peak

pressure shifted back and forth. The density of the plasma will be determined. In Fig. 10 the picture of the plasma column entering the magnetic field indicates that the dense plasma indeed stayed together as a small diameter beam. The sequence of pictures can be compared with diamagnetic coil data. The dark band is the No. 4 diamagnetic coil. At 4 μsec the fast plasma started to penetrate the magnetic field opening. The horn shape of the flux lines guiding the flowing plasma can be seen. At 5 μsec the plasma also can be seen as if it had just passed Coil No. 5, and the dense plasma had cumulated just beyond Coil No. 5. This corresponds to the small hump of the signal ahead of the build-up. At 6 μsec , part of the plasmas were reflected back and part of them went further inside the coil. The plasma had higher density with the arrival of the continuous flow Z-pinch plasma. This plasma forced open the field lines so that most of the plasmas could be penetrated from 8 μsec onward up to 12 μsec . In the meantime, some of the fast plasma from the other gun also escaped from the field. This was shown as a concentric cylinder of different density plasmas. After 14 μsec only escaping plasmas were presented. The small diameter of the plasma beam resulting from the continuous flow Z-pinch made possible almost no scattering of the plasmas to penetrate into the mouth of the field.

The density of the plasma can be evaluated from diamagnetic probe data. Since the plasma can form a bottle configuration which is due to the diamagnetic property of the plasma (Fig. 11), the following assumptions can be made: (1) The plasma had a β build-up to 1 with a finite diameter and then remained to be 1

with increasing diameter, (2) The temperature of the plasma was increased from recovering their kinetic energies. The velocities of the plasma front (greater than 2×10^8 cm/sec) and the continuous flow plasma (about 4.5×10^7 cm/sec) were measured from the streak pictures. The average velocity of the plasma is assumed to be 5×10^7 cm/sec. From earlier data, the flowing plasma had a temperature of about 75 ev (Ref. 3), so the stagnated plasmas would have a temperature of 215 ev. This temperature is estimated by taking into account the three degrees of freedom for a $\beta = 1$ plasma. The pressure of the plasma was calculated from the equilibrium assumption,

$$P = \frac{B_m^2}{8\pi}$$

where $B_m = B_o + \Delta B$, with B_o being the original D.C. B_z field. ΔB is the increasement of magnetic flux density and can be calculated so that the diamagnetic coil signals measured the amount of magnetic flux being displaced across the diamagnetic coil.

From the conservation of the total flux lines,

$$B_o \pi r_o^2 = \Delta B \pi (R^2 - r_o^2)$$

r_o is the radius of the confined plasma, R is the radius of the coil,

so

$$r_o^2 = \frac{\Delta B}{B_o + \Delta B} R^2$$

The amount of flux lines pushed across the diamagnetic coil are $B (R^2 - r_o^2)$ which can be evaluated from the integral diamagnetic signals. With this, the plasma pressure

$$P = \frac{(B_o + \Delta B)^2}{8\pi} = \frac{B_o^2}{8\pi} \left(\frac{R^2}{R^2 - r_o^2} \right)^2 = \frac{B_o^2}{8\pi} \left(\frac{B_o + \Delta B}{B_o} \right)^2$$

With temperature $T = 215$ ev, the density can be obtained. The time history of the plasma is shown in Fig. 10.

The neutron production period with the magnetic field was very long, and the bouncing of the plasma blob along the Z-axis created bursts of neutrons. In order to compare the effect of the magnetic field, many numbers of firings were done without the magnetic field. The time resolved neutron signals with and without the field are shown in Fig. 12. The top trace has a neutron signal with a field about 9 kilogauss. The bottom trace has a burst of neutron for the fast plasma interaction although the neutron source could not be exactly located. No neutron burst can be seen after this. A silver activated neutron counter was also used in conjunction with a counter printer unit. The counting was printed every minute. This enables us to check the background counts before and after the firing. The average of the neutron production, over 16 firings, indicated a significant increase in the neutron production with the magnetic field.

The experiment of double injection of the plasmas into a long B_z field was the first of its kind. The amount of time and support level can only allow us to do this in a small machine; however, the results indicate no gross instability, as in the case of the lower density injection experiments. The confirmed plasma density $10^{15}/\text{cc}$ is three orders of magnitude better than other injection experiments. The high density together with the long confinement time were made possible because of the unique plasma deflagration gun. This certainly suggests many possible experiments in a similar but larger machine in the future. Some day we certainly hope to break the barrier of Lawson's criteria. Other applications of this experiment include the chalking of the

plasma leakage of the θ -pinch machine and injection of dense plasma into other configurations.

PUBLICATIONS DURING THE LAST SIX MONTHS:

1. D. Y. Cheng, "Preliminary Study of the High Pressure Confinement of a Z-Pinch, Theory and Some Experimental Results", Proceedings of the Second International Conference on High Beta Pulsed Plasma, Garching, Germany, July 1972, pp. 217-220.
2. D. Y. Cheng and P. Wang, "The Properties of a Coaxial Deflagration Plasma Gun", Proceedings of the Second International Conference on High Beta Pulsed Plasma, Garching, Germany, July 1972, pp. 257-260.
3. D. Y. Cheng, "A Preliminary Study of the Formation of a Fusionable Plasma in a High Pressure Arc Channel", submitted to Nuclear Fusion.
4. D. Y. Cheng and P. Wang, "High Density Plasma Beam Formation of the Continuous-Flow Z-Pinch", submitted to Nuclear Fusion.
5. P. Wang and D. Y. Cheng, "Double Injection and Confinement of Dense Plasma Inside a D.C. B Field", Plasma Physics Div. Meeting, APS, Nov. 13-16, 1972.

ACKNOWLEDGMENT:

We are grateful to Mr. Howard A. Stine for his support of this work during the past three years. Also, we are grateful for the technical support of Mr. George Giorgetti. Their contributions were the main posts supporting this experiment.

The authors are also indebted to Mr. William A. Carlson and Mrs. James A. Jedelicka for their constant help in consulting.

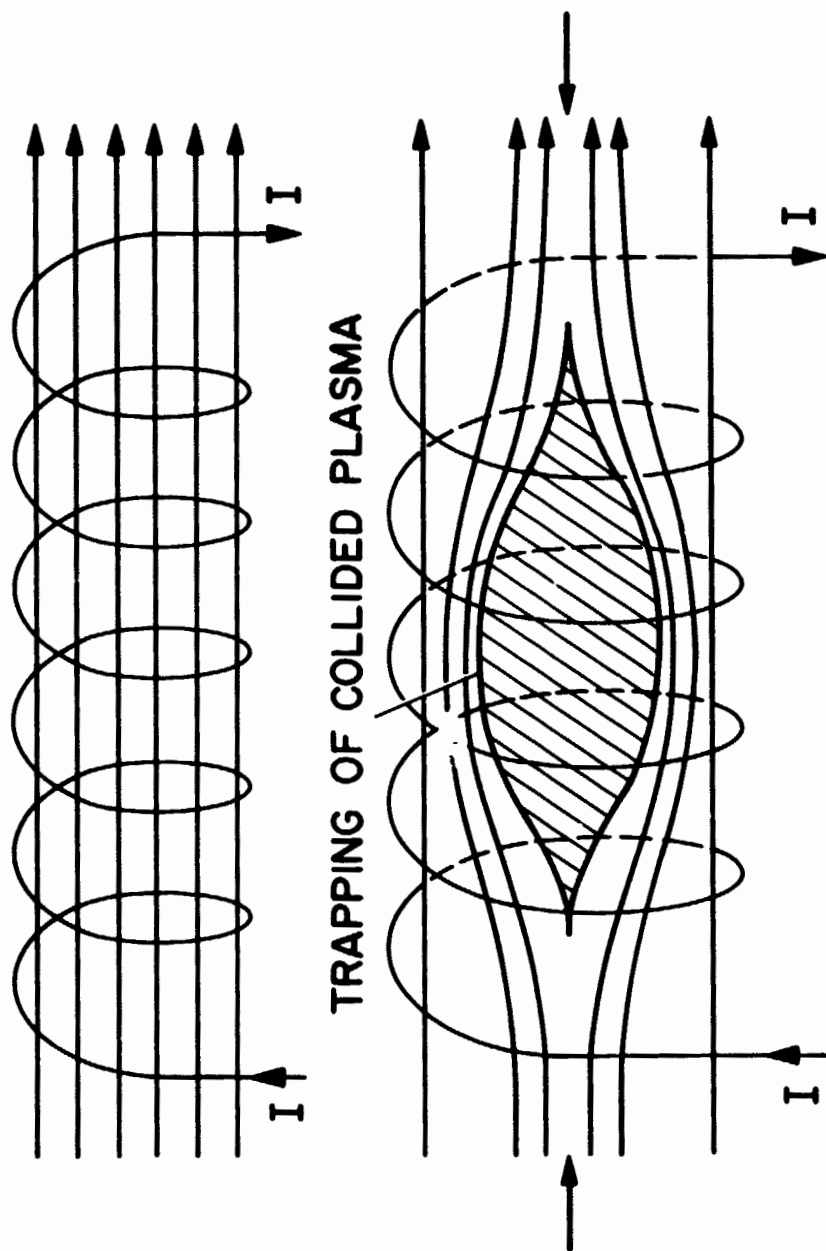
REFERENCES:

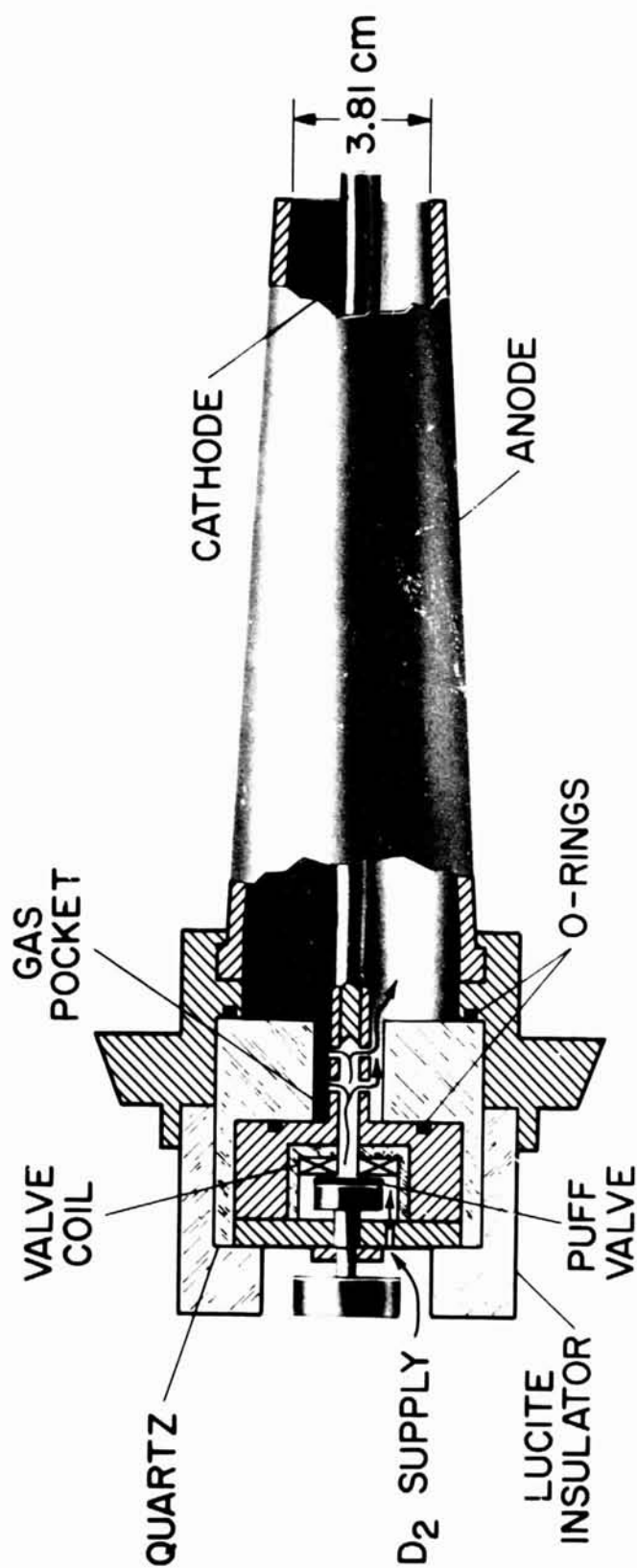
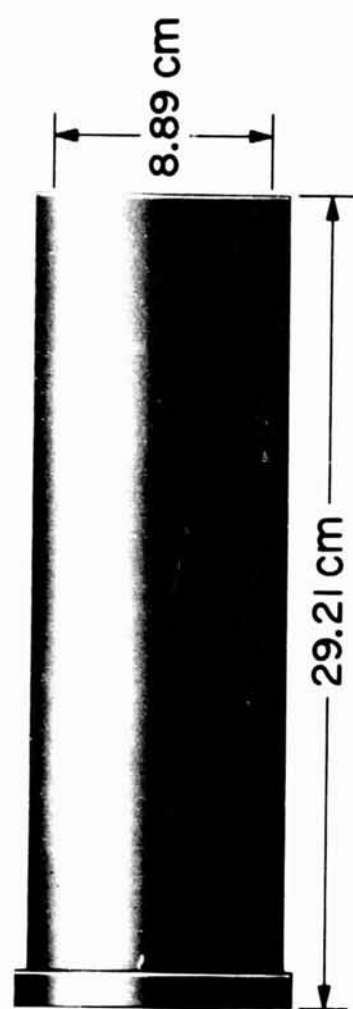
1. Coensgen, F. H., F. C. Ford and R. E. Ellis, Proceedings of the Second U.N. Conference on Peaceful Uses of Atomic Energy, 32, 1958, p. 266.
2. Cheng, D. Y., Nuclear Fusion, 10, 1970, pp. 305-351.
3. Cheng, D. Y., J. AIAA, 9, 1971, pp. 1681-1685.
4. Cheng, D. Y., and P. Wang, Proceedings of the Second International Conference on High Beta Pulsed Plasma, Garching, Germany, 1972, pp. 257-260.

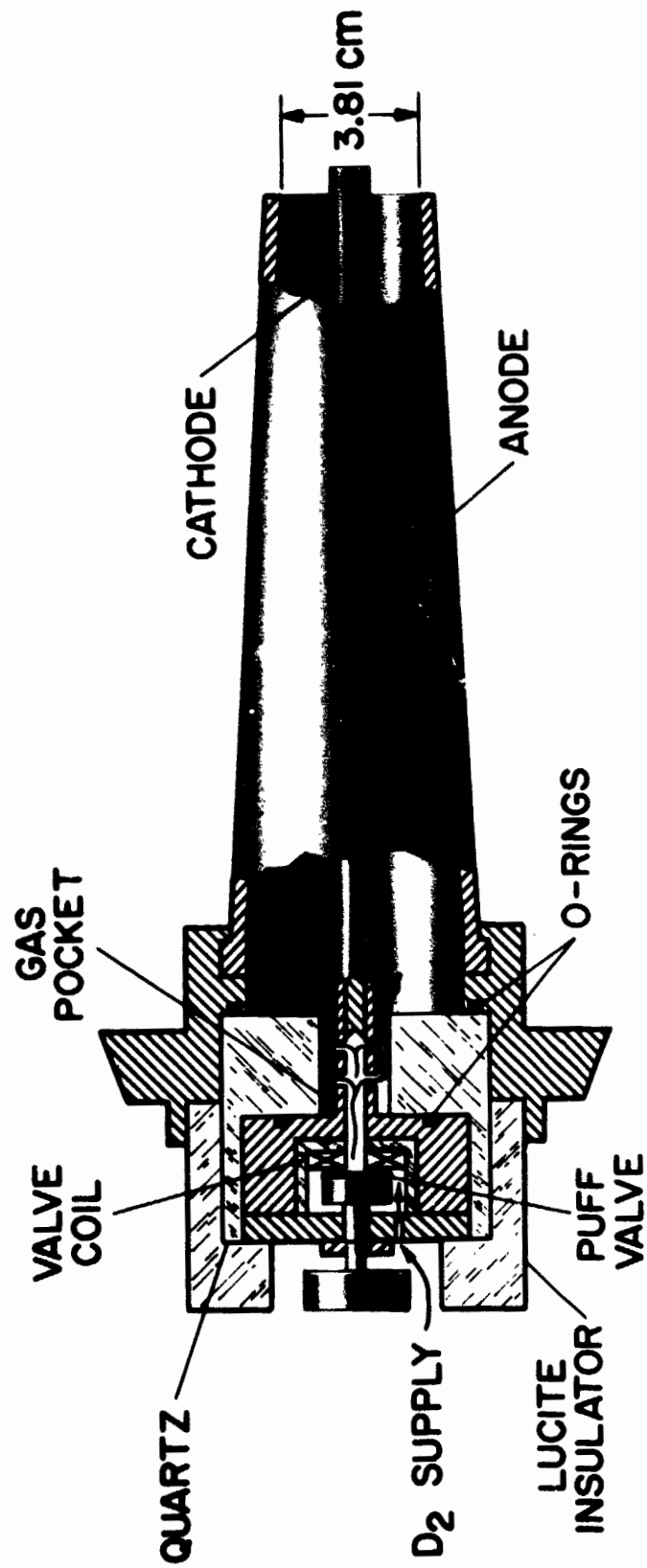
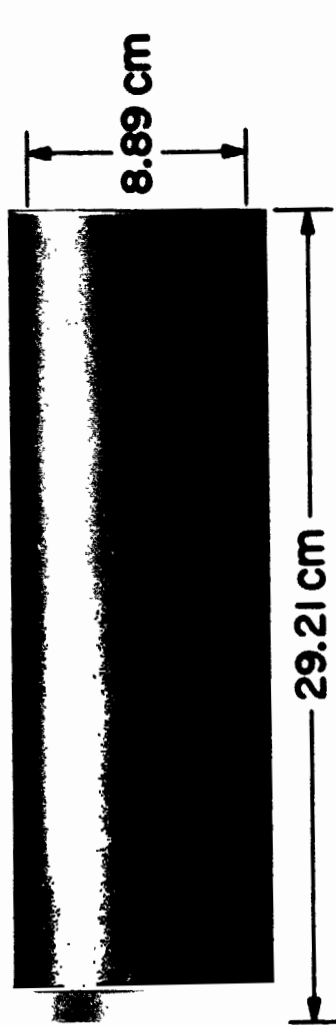
5. Morozov, A. I., A. Tek. Fiz., 37, 12, 1967, p. 2147.
6. Azizov, E. A., V. S. Komelkov and M. M. Stepanenko, Z. Tek. Fiz., 42, No. 1, 1972, p. 203.
7. Fellippova, T. I., N. V. Fillipov, and V. P. Vinogradov, Nuclear Fusion, Suppl., Part 2, 1962, p. 577.
8. Aretov, G. N., J. N. Burdonsky, Yu. A. Volkov, V. I. Vasiljev, A. P. Lototsky, Y. V. Skvotsov, V. G. Solovjova and Yu. F. Suslov, Proceedings of the Second International Conference on High Beta Pulsed Plasma, Garching, Germany, July 1972, Paper No. E11, Germany, 1972.

CAPTION OF FIGURES

1. Thermalized Plasmas in a Self-Imposed Magnetic Bottle.
2. Deflagration Plasma Gun.
3. Time History of the Development of the Continuous Flow Z-Pinch from the Deflagration Plasma Gun.
4. (a) Ordinary B_z Field, (b) Inverted B_z Field.
5. Set Up of the Injection Experiment.
6. Illustration of the Instrumentation of the Injection Experiment.
7. Streak Picture of the Plasma Collision Trapping and Confinement.
8. (a) Gun Valve Current Trace, (b) Gun Discharge Current Trace, (c) Diamagnetic Coil Signal Trace #4 and #5, 0.2 V/cm with Integrator Time Constant = 2.2 millise., #6 and #7, 5 V/cm with Integrator Time Constant = 940 μ sec, (3) Time Resolved Neutron Signal, (e) Streak Picture, 10 μ sec Streak Duration, Delayed 25 μ sec after Gun #1 Started.
9. Diamagnetic Coil Signal as Evaluated in Terms of Plasma Pressure.
10. 50 nanosec Exposure of the Plasma Penetrating the Entrance Region of the Magnetic Field as a Function of Time.

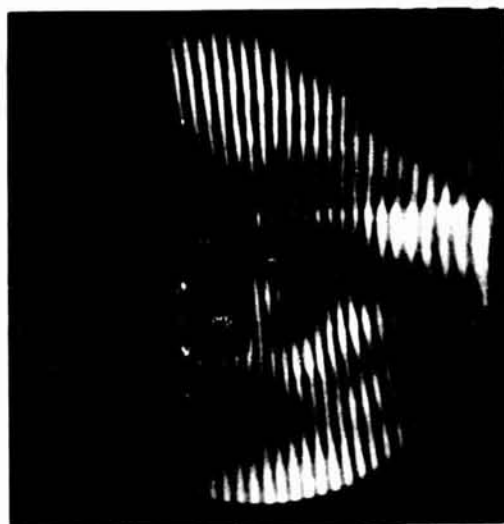




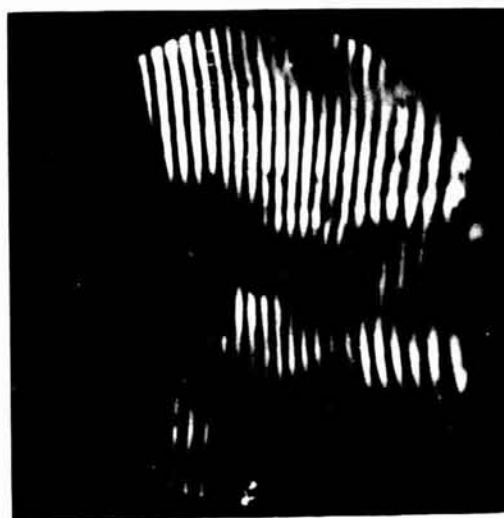


μsec

-1.5



2.7

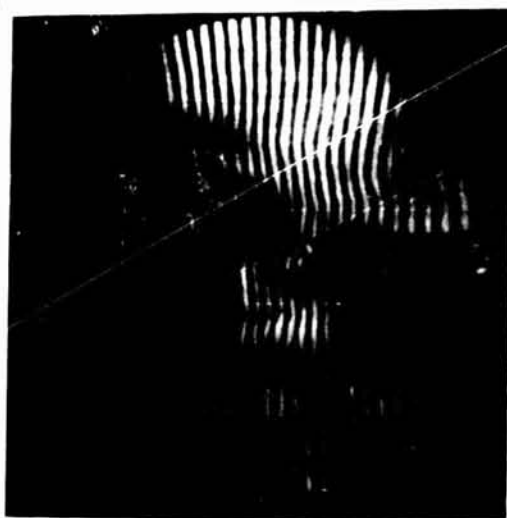


4.5



μsec

6.0

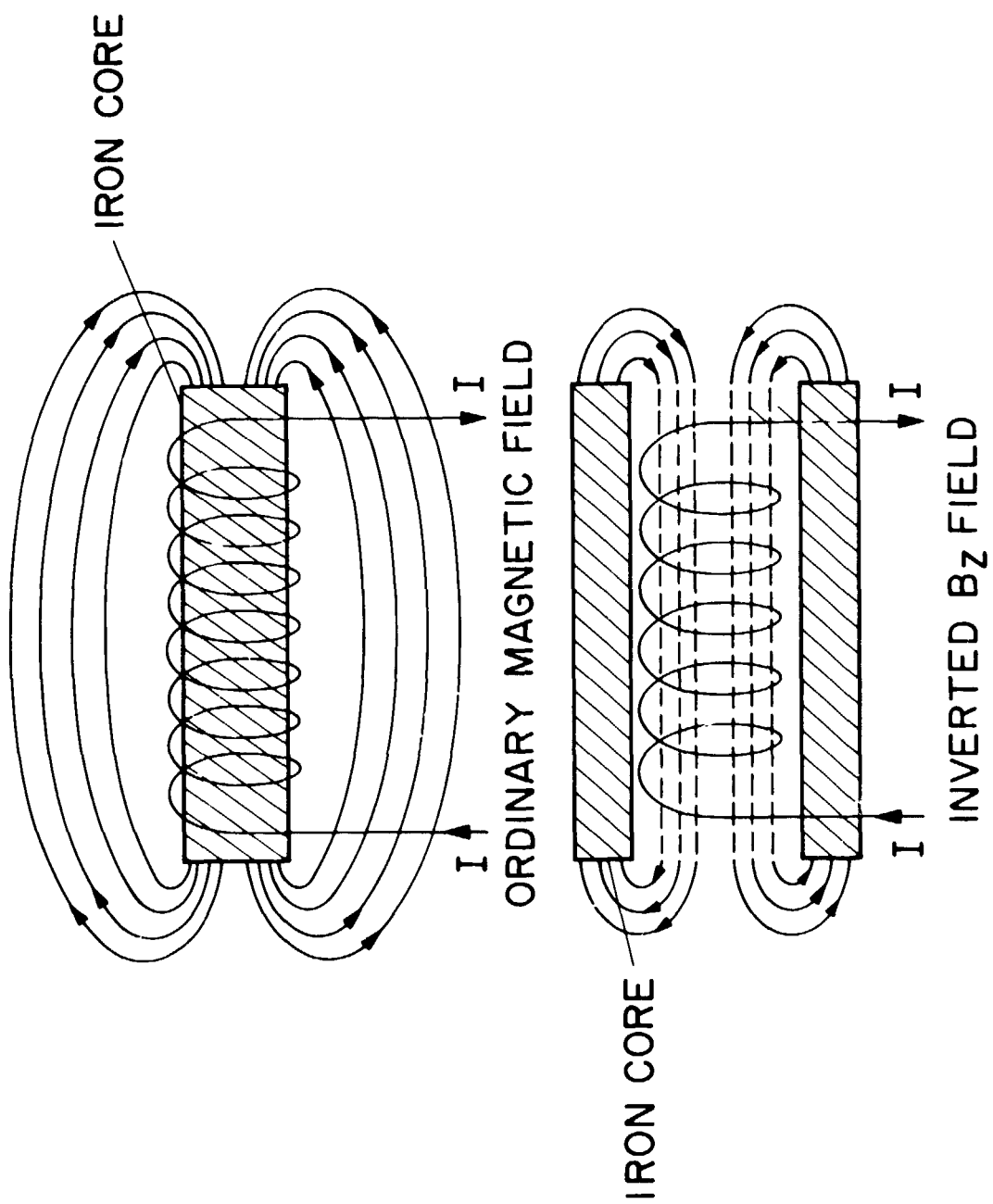


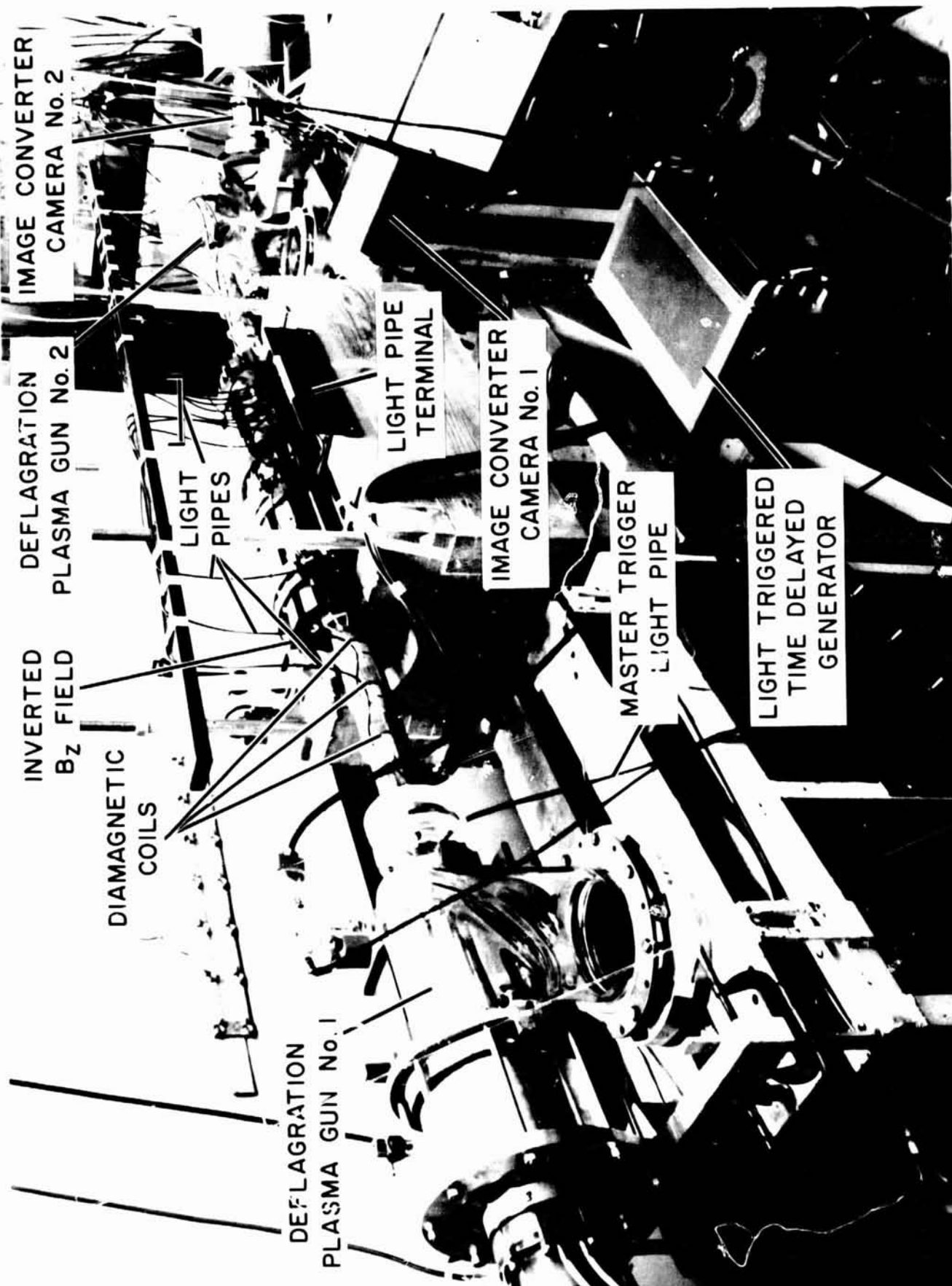
9.0



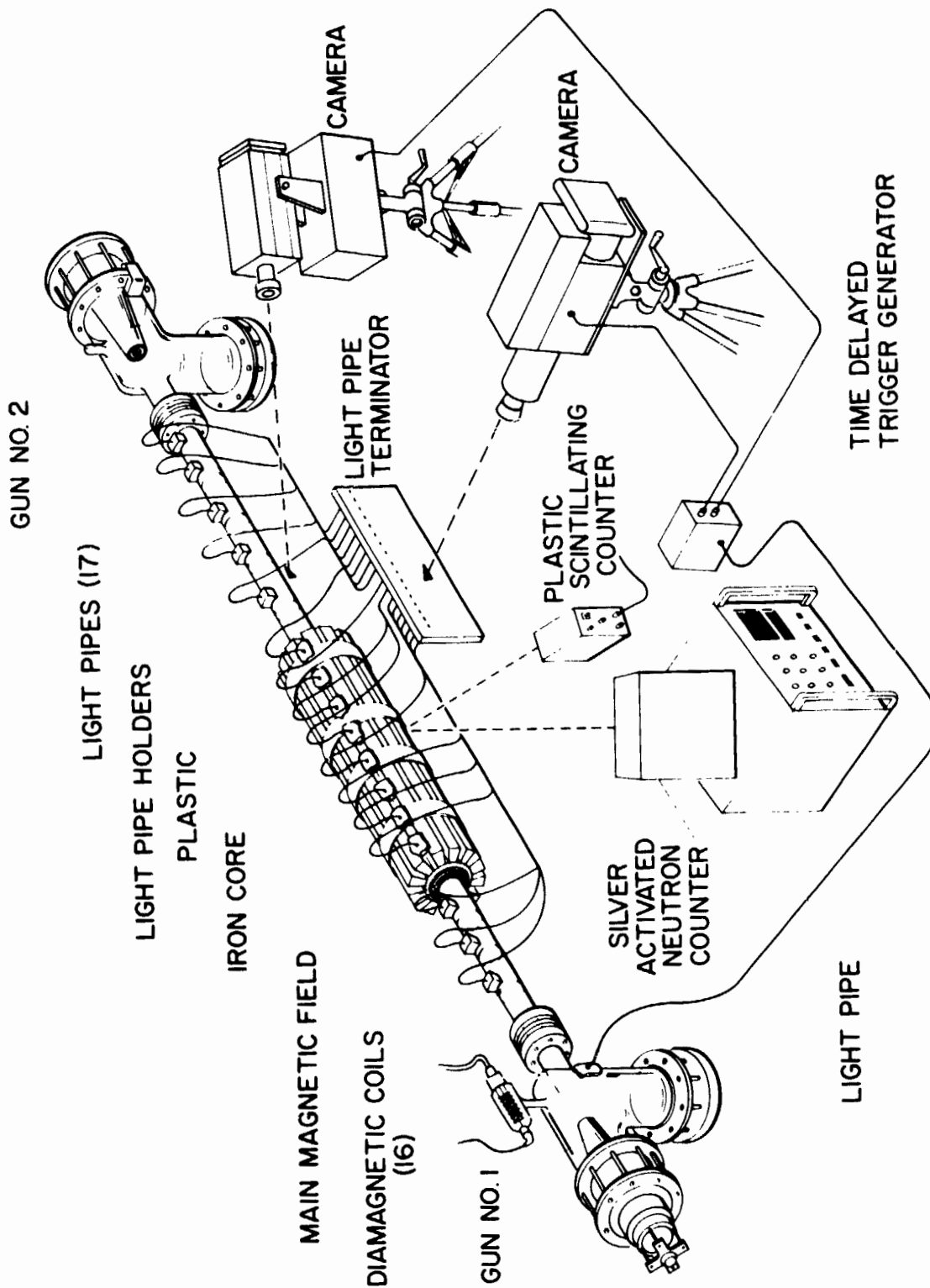
11.3







PHOTOGRAPH BY J. R. HARRIS, JR.
FOR THE U.S. AIR FORCE



FAST PLASMA
COLLISION,
 $3.5 \mu\text{sec}$

SLOWER
PLASMA
COLLISION,
 $6.1 \mu\text{sec}$

CONTINUOUS
BUILDUP OF
THE PLASMA
DENSITY

SLOW DECAY OF
THE CONFINED
PLASMA

$10 \mu\text{sec}$

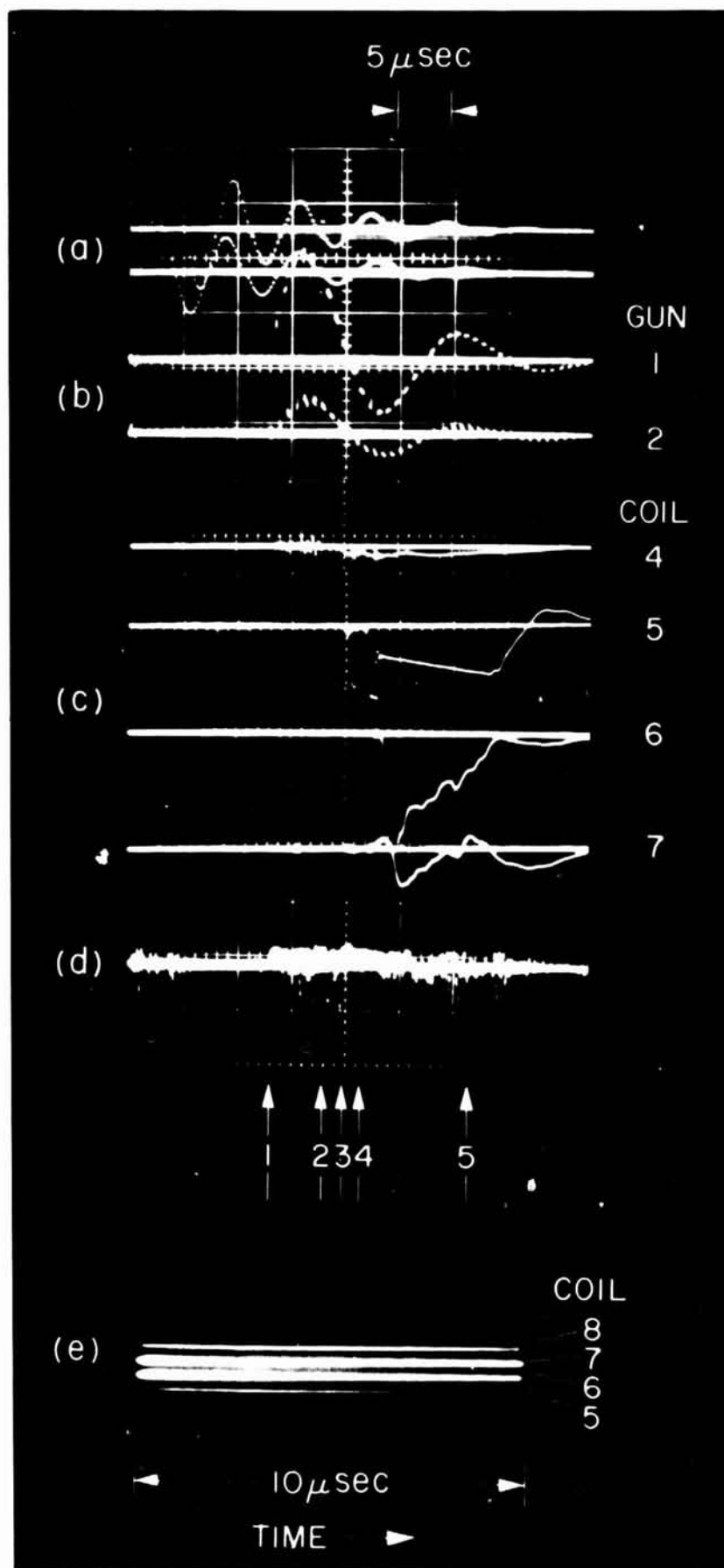
NO
DELAY

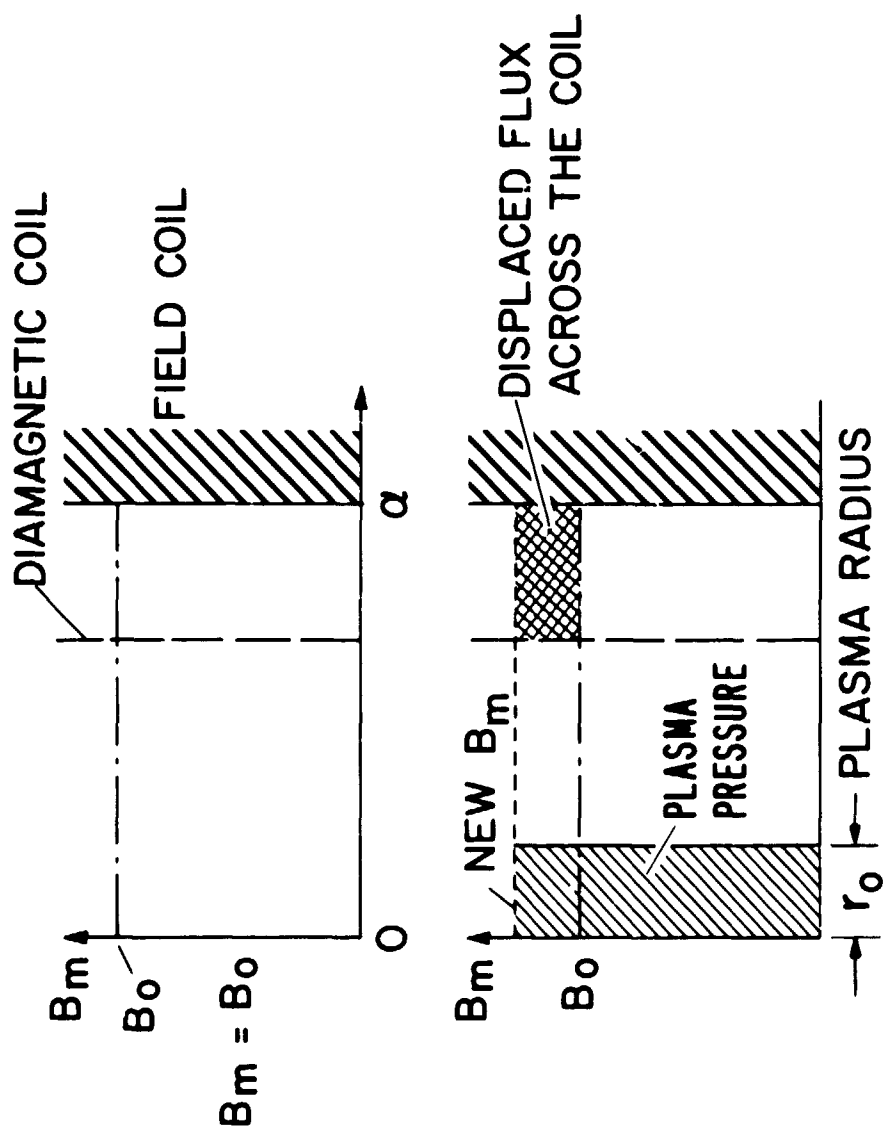
$10 \mu\text{sec}$

DELAYED
 $5 \mu\text{sec}$

$10 \mu\text{sec}$

DELAYED
 $15 \mu\text{sec}$





μSEC

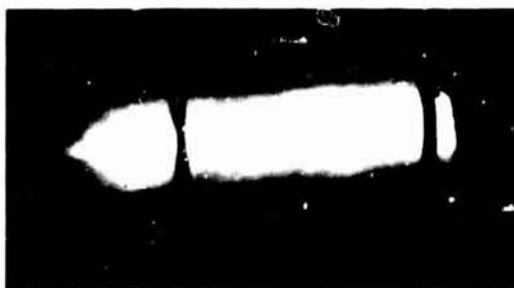
10



11



12



13



14



